

# DRIVEN EQUILIBRIUM AND FAST-SPIN ECHO SCANNING

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## Cross Reference to Related Application

This is a continuation-in-part of co-pending U.S. patent application no. 09/769,446, which was filed on January 26, 2001. Priority is also claimed under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application Serial No. 60/309,479, which was filed on August 3, 2001.

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## Field of the Invention

In general, the present invention relates to methods of performing nuclear magnetic resonance (NMR) imaging. In particular, the present invention is a method of reducing the scan time in performing NMR imaging by utilizing driven equilibrium and fast-spin echo techniques, which in turn enables improved scanning and imaging operations.

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## Background of the Invention

Magnetic resonance imaging (MRI) is one of the most versatile and fastest growing modalities in medical imaging. Since the discovery by Dr. Raymond Damadian in the early 1970s that nuclear magnetic resonance techniques can be used to scan the human body to yield useful diagnostic information, medical NMR imaging devices have been developed for obtaining NMR images of the internal structures of patients. Subsequently, much effort has been expended to improve and refine the techniques used for obtaining NMR images, as well as to

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determine the diagnostic utility of NMR images. As a result, NMR imaging, or magnetic resonance imaging, as it is sometimes known, has today proven to be an extremely useful tool in the medical community for the purposes of detecting and diagnosing abnormalities within the body.

5           Conventional magnetic resonance imaging techniques generally utilize pulsed magnetic field gradients to spatially encode NMR signals from various portions of an anatomical region of interest. The pulsed magnetic field gradients, together with radio frequency excitation of the nuclear spins and acquisition of signal information, are commonly referred to as a pulse sequence.

10           The basic science behind NMR imaging is as follows. Pulsed current through a set of conductors will produce a magnetic field external to the conductors; the magnetic field generally has the same time course of development as the current in the conductors. The conductors may be distributed in space to produce three orthogonal gradients: X, Y, and Z. Each of  
15 the gradients may be independently pulsed by a separate time-dependent current waveform.

20           In order to construct images from the collection of NMR signals, conventional NMR imaging equipment generally utilizes magnetic field gradients for selecting a particular slice (volume) or plane of the object to be imaged and for encoding spatial information into the NMR signals. For example, one conventional technique involves subjecting an object to a continuous static homogenous field extending along a first direction, and to sets of sequences of orthogonal magnetic field gradients. Each set of orthogonal magnetic field

gradient sequences generates a magnetic field component in the same direction as the static field, but the gradients have strengths that vary along their directions.

Generally, the NMR phenomenon occurs in atomic nuclei having an odd number of protons and/or neutrons. Due to the spins of the protons and neutrons, each such nucleus exhibits a magnetic moment. As a result, when a sample composed of such nuclei is placed in the homogeneous magnetic field, a greater number of nuclear magnetic moments align with the direction of the magnetic field to produce a net macroscopic magnetization in the direction of the field. Under the influence of the magnetic field, the magnetic moments precess about the axis of the field at a frequency that is dependent upon the strength of the applied magnetic field and on the characteristics of the nuclei. The angular precession frequency,  $\omega$ , also referred to as the Larmor frequency, is given by the equation  $\omega = \gamma B$ , where  $\gamma$  is the gyro-magnetic ratio (which is a constant for each particular atomic nucleus) and  $B$  is the strength of the magnetic field acting upon the nuclear spins.

When a substance such as human tissue is subjected to a uniform magnetic field (polarizing field  $B_0$ ), the individual magnetic moments of the spins in the tissue attempt to align with this polarizing field, but the randomly-oriented magnetic components in the perpendicular (transverse) plane (X-Y plane) cancel one another. If, however, the tissue is also subjected to a magnetic field (excitation field  $B_1$ ) that is in the X-Y plane and that is at the Larmor frequency, the net aligned moment,  $M$ , may be rotated, or "tipped", into the X-Y plane to

produce a net transverse magnetic moment  $M_t$ .  $M_t$  rotates, or spins, in the X-Y plane at the Larmor frequency. The practical value of this phenomenon resides in the signal that is emitted by the excited spins after the excitation field  $B_1$  is removed.

5        Thus, the orientation of the moment (also known as the magnetization)  $M$  can be perturbed by the application of a magnetic field oscillating at the Larmor frequency, which has the effect of rotating the magnetization away from the direction of the static field. Typically, the oscillating magnetic field is applied in a direction orthogonal to the direction of the static magnetic field by means of a  
10        radio frequency (RF) pulse through coils connected to a radio frequency transmitting apparatus. In essence, the net magnetic vector or orientation of magnetization  $M$  is rotated away from the direction of the static field. One typical  
15        RF pulse is that which has either sufficient magnitude or duration to rotate the magnetization  $M$  into a transverse plane (that is, 90 degrees from the direction of the static field) and thus is known as a 90-degree RF pulse. Similarly, if the magnitude or duration of the RF pulse is selected to be twice that of a 90-degree pulse, the magnetization  $M$  will change direction 180 degrees from the main or static magnetic field, and the excitation pulse is called a 180-degree RF pulse.

      Accordingly, a typical imaging procedure involves the use of three  
20        orthogonal magnetic field gradients, X, Y, and Z, which are pulsed coordinately along with bursts of radio frequency energy. For example, the Z gradient is pulsed on for two brief time periods. A 90-degree radio frequency pulse in the first time period and a 180-degree radio frequency pulse in the second time

period are used to select a slice of the anatomy of interest, and to induce the nuclear spin system within that slice to generate an NMR signal. Once the slice is selected by the Z gradient, the two remaining orthogonal gradients are used to confer spatial encoding on the NMR signal in the two orthogonal directions. For example, the Y gradient will encode on the basis of phase advances imparted on a series of signal responses by using a pulsed gradient waveform of progressively increasing area. The X gradient, which is pulsed on during the signal collection period, will frequency-encode the NMR signal in the third orthogonal direction.

When the RF excitation pulse is stopped (by turning the RF transmitter off), the nuclear spins tend to slowly realign or relax back to the equilibrium position. At this time, the spins emit an NMR signal, which can be detected with an RF receiver coil (which may be, and often is, the same coil as that used with the transmitter). The emitted NMR signal is dependent on three basic parameters, namely, the density of the excited nuclei, the spin-lattice (longitudinal) relaxation time ( $T_1$ ), and the spin-spin (transverse) relaxation time ( $T_2$ ). The latter two parameters are both exponential time constants that characterize the rate of return to equilibrium of the longitudinal and transverse magnetization components following the application of the perturbing RF pulse. These NMR parameters of spin density,  $T_1$  and  $T_2$ , are related to the atomic nuclei subjected to the NMR phenomenon.

In accordance with this technique, nuclear spins in a selected plane are excited by a selective RF pulse, in the presence of one of the magnetic field

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gradients. The frequency of the selective RF pulse corresponds to the Larmor  
frequency for only the selected plane of the object as determined by the  
magnetic field gradient imposed on the static magnetic field. The applied  
magnetic field gradient is designated as the slice-selection gradient. The  
5 selected plane will therefore extend in a direction perpendicular to the gradient  
direction of the slice-selection magnetic field gradient. The selected spins are  
then subjected to the other magnetic field gradients (which can be designated as  
the read-out and phase-encoding magnetic field gradients). A plurality of  
repetitions are utilized in which the amplitude of the phase-encoding gradient is  
10 varied for each repetition and in which the read-out gradient is applied during the  
reading out of the generated NMR signals.

The NMR signal is processed to yield images that give an accurate  
representation of the anatomical features in the selected slice, as well as provide  
excellent soft tissue contrast. NMR signals may be processed using various  
15 algorithms, depending upon the precise nature of the data acquisition procedure.  
However, all methods employed rely on the ability to spatially encode the signal  
information by making use of the magnetic field gradients, which are time  
modulated and sequentially pulsed in various modes to effect the desired result.

For example, the received NMR signals may be transformed by utilizing,  
20 for example, conventional two-dimensional Fourier transform techniques. The  
read out magnetic field and phase-encoding magnetic field gradients encode  
spatial information into the collection of NMR signals so that two-dimensional  
images of the NMR signals in the selected plane can be constructed. During the

scanning sequence, the various magnetic field gradients are repeatedly switched on and off at the desired intervals.

Many NMR imaging schemes rely on a collection of spin-echo NMR signals. In utilizing spin-echo signals, a 90-degree RF excitation pulse is followed by the application of a 180-degree rephasing RF pulse at a predetermined time interval after the 90-degree pulse. This produces a spin-echo signal at a corresponding time interval after the application of the 180-degree RF pulse. In NMR parlance, the time that the spin-echo NMR signal is produced after the 90-degree RF excitation pulse is designated as TE (for time of echo). Thus, the 180-degree RF pulse is applied at a time interval of TE/2 after the 90-degree RF pulse.

In the application of NMR principles to medicine and medical diagnostic imaging of live human subjects, NMR signals are obtained for a multitude of small areas in a patient, known as picture elements or pixels. The pixels are used to construct an image or pictorial representation of a particular area of the patient being examined. More particularly, the intensity of the NMR signals is measured for the multitude of pixels. The intensity of each signal is a complex function of the tissue-related parameters used in gathering the image information.

For example, it is known that variations in the relaxation times T1 and T2 are closely associated with the differences between healthy and diseased tissue, and thus, from a diagnostic viewpoint, images that display or show significant T1 and/or T2 contrast have proven to be of great diagnostic interest. Unfortunately,

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in conventional techniques for obtaining both T1-weighted data and T2-weighted data, not only are separate scans required for obtaining T1-weighted and T2-weighted images, but further, additional T1-weighted scans are required to obtain T1-weighted images for the same number of slices for which T2-weighted scans are obtained. This increases the number of scans of the patient that must be performed and the time necessary to complete such scans. After each imaging scan that is performed on a patient, it is generally necessary to allow the patient to rest. Also, a certain amount of time is necessary when conducting a scan for operator setup, loading information into the apparatus with respect to the conditions and sequencing for collection of data, etc. Therefore, in order to obtain, using conventional techniques, T2-weighted images for a plurality of planes and a corresponding number of T1-weighted images, the total scanning time is quite long. It is apparent that one of the major problems with medical NMR imaging is patient throughput. Thus, numerous efforts have been devoted to the development of techniques for obtaining images in a shorter period of time.

Although various efforts have been devoted to the development of techniques for shortening the scan times, to date, they have generally resulted in a sacrifice of the diagnostic quality of the information obtained, and thus, have not yet proven satisfactory.

One factor contributing to the length of an imaging time period is the period of time required for the return of the nuclear magnetizations to equilibrium prior to the subsequent excitation. A method that has been used to shorten this time period is known as the driven equilibrium pulse technique. In typical driven



equilibrium techniques utilized with spin-echo sequences, spins in the X-Y plane are driven back to alignment with the Z-axis in order to shorten the time period required for the spins to return to equilibrium. As a result, the data acquisition time is shortened, and image contrasts may be manipulated in pulse sequences at a high repetition rate.

However, driven equilibrium techniques have not become a standard on clinical scanners. A major problem with conventional driven equilibrium techniques is the resulting lack of contrast control in the derived image. Some of the difficulty may be related to eddy current control and RF phase control in MRI scanners. That is, in order to obtain accurate diagnostic information using the conventional driven equilibrium technique, it is important that all the spins in the selected slice are precisely in phase, and that the 90-degree Z-restoring pulse is delivered along an axis that is exactly perpendicular to the direction along which the transverse magnetization is focused. Even small deviations in these parameters caused by eddy currents generated by the gradients are enough to seriously degrade the amount of magnetization restored to the Z-axis.

Another technique for decreasing the scan and image capture time of an NMR imaging procedure is the use of fast-spin echo methods. Such methods involve the acquisition of multiple spin-echo signals from a single excitation pulse in which each acquired echo signal is separately phase-encoded. Each pulse sequence therefore results in the acquisition of a plurality of views, and a plurality of pulse sequences is typically utilized to acquire a complete set of image data.

However, using such techniques, although the TE time interval can be varied, the repetition rate is the same for each produced image.

In an effort to improve scanning throughput, most conventional scan methodologies utilize multiple-slice techniques. In a multiple-slice scan procedure, a patient must remain stationary throughout a prolonged scan process, during which an entire sequence of slices is captured. Patients often get uncomfortable during this process, and may fidget or move involuntarily. These movements, however small, create motion artifacts that make diagnosis difficult, or even impossible. This effect is particularly significant in a multi-slice process, because if a patient moves at any time, all the slices will show the motion artifacts and the entire scan procedure will have to be repeated.

This effect is more prevalent when performing a standing MRI scan, during which the patient is asked to stand during the scanning procedure. Images show dramatic differences in anatomy, due to the different weight-bearing qualities present in the human body, when a person is standing compared to when he or she is recumbent. In many cases, much greater anatomical detail is shown in a standing scan, and causes of a patient's symptoms that would go undiagnosed if the patient is scanned in a lying position might be correctly identified if the same patient is scanned while standing. Thus, there may be great benefit to having a patient stand during the scanning procedure.

However, standing for the duration of a multiple-slice scan procedure is even more demanding than during an imaging session that is conducted while

the patient is lying down. A standing patient is more likely to become fatigued, and to fidget or shift his or her weight during the course of the scan. Because the patient is likely being scanned to analyze a physical ailment, he or she would probably have difficulty in enduring a standing multiple-slice procedure. Thus, in order to take advantage of the benefits offered by scanning a standing patient, it is necessary to speed up the scanning procedure.

Conventional multiple-slice scan procedures have other drawbacks as well. For example, the distance between slice boundaries in the direction of the thickness of the slices must be limited, in order to avoid saturation. A result of closing the gap between slice boundaries is a drop in signal-to-noise ratio, which in turn leads to images having a resolution that is unsuitable for reliable medical diagnosis. A larger inter-slice boundary, however, also lessens the utility of the slice images and the dependability of the resulting analysis.

Accordingly, a significant need exists for shortening the time period for obtaining the T1-weighted and T2-weighted images, and in particular, to reduce the total acquisition time for acquiring the data and information from which T1-weighted and T2-weighted NMR images are constructed. Further, there is a need for an overall scanning methodology that can provide for more closely-spaced slice acquisition data.

## Summary of the Invention

It is therefore an objective of the present invention to provide a reduced scanning and image data collection time for NMR imaging, without sacrificing image quality.

5 It is a further objective of the present invention to provide a scanning procedure that makes it more practical to perform stand-up MRI scans.

It is an additional objective of the present invention to provide a scan methodology by which scanned images include detail necessary to make more reliable patient diagnosis.

10 These and other objectives and advantages of the present invention will be apparent on reading the following written description, as summarized below.

According to an aspect of the invention, an NMR imaging process includes subjecting an imaging object to a uniform polarizing magnetic field, applying orthogonal magnetic field gradients to the imaging object, applying RF energy to the imaging object according to a fast-spin echo technique, subsequently  
15 applying RF energy to the imaging object according to a driven equilibrium technique, detecting a nuclear magnetic resonance signal emitted by the imaging object, and processing the nuclear magnetic resonance signal to provide diagnostic information. The diagnostic information may be imaging data.

20 Applying RF energy to the imaging object according to a fast-spin echo technique may include applying an RF pulse corresponding to the angular precession frequency for a selected slice of the imaging object. The diagnostic information may be provided to a presentation device such that a visual image corresponding

to the imaging object can be viewed by an operator, so that a subjective determination can be made as to whether the visual image is of good quality or bad quality. An RF pulse corresponding to a different angular precession frequency may be applied, to select a respective different slice of the imaging object, if the subjective determination is that the visual image is of good quality. The respective different slice of the imaging object may be an adjacent slice of the imaging object, in which case the selected slice and the adjacent slice may overlap to an extent that is greater than 0% and less than or equal to 100%. Another RF pulse corresponding to the angular precession frequency may be applied, to select the same slice of the imaging object, if the subjective determination is that the visual image is of bad quality. Alternatively, the diagnostic information may be tagged, if the subjective determination is that the visual image is of bad quality. In that case, an RF pulse corresponding to a different angular precession frequency may be automatically applied, to select a respective different slice of the imaging object. The respective different slice of the imaging object may be an adjacent slice in a sequence of slices of the imaging object, in which case the selected slice and the adjacent slice may overlap to an extent that is greater than 0% and less than or equal to 100%. An RF pulse corresponding to a final angular precession frequency may be applied, to select a final slice in the sequence of slices of the imaging object, and an RF pulse corresponding to the angular precession frequency may be applied that corresponds to the tagged image data. The imaging object may be a human being, and the uniform polarizing magnetic field may be produced by a magnetic

resonance imaging system. The human being may stand upright within the uniform polarizing magnetic field. After providing the diagnostic information, the imaging object may be moved and an RF pulse corresponding to the same angular precession frequency may be applied, to select a different slice of the imaging object. Moving the imaging object may include changing the angle of the imaging object with respect to the uniform polarizing magnetic field. The fast-spin echo technique may include application of a multi-echo NMR imaging sequence. The multi-echo NMR imaging sequence may include a plurality of different echoes, and each of the plurality of different echoes may be encoded differently. The multi-echo NMR imaging sequence may include a plurality of different echoes, and at least one of the plurality of different echoes may be encoded differently than another one of the plurality of different echoes. A 90-degree RF pulse may be applied at the center of any of the plurality of different echoes, and the applied 90-degree RF pulse may have a phase such that magnetization of the imaging object is forced in the direction of the uniform polarizing magnetic field. The multi-echo NMR imaging sequence may include a first 90-degree RF pulse followed by a series of 180-degree RF pulses, and the series of 180-degree RF pulses may include  $n$  180-degree pulses, followed by  $n$  echoes. A second 90-degree RF pulse may be applied at a center of the  $n$ th echo, such that magnetization of the imaging object is oriented in the direction of the uniform polarizing magnetic field.

According to another aspect of the present invention, an NMR imaging process includes subjecting an imaging object to a uniform polarizing magnetic

field, applying orthogonal magnetic field gradients to the imaging object, applying a first 90-degree RF excitation pulse, applying a sequence of 180-degree RF excitation pulses following the first 90-degree RF excitation pulse, applying a second 90-degree RF excitation pulse following the sequence of 180-degree RF excitation pulses, detecting a nuclear magnetic resonance signal emitted by the imaging object, and processing the nuclear magnetic resonance signal to provide diagnostic information. The diagnostic information may be imaging data. The first 90-degree RF excitation pulse may correspond to the angular precession frequency for a selected slice of the imaging object. The diagnostic information may be provided to a presentation device such that a visual image corresponding to the imaging object can be viewed by an operator, so that a subjective determination of whether the visual image is of good quality or bad quality can be made. An RF pulse corresponding to a different angular precession frequency may be applied, to select a respective different slice of the imaging object, if the subjective determination is that the visual image is of good quality. The respective different slice of the imaging object may be an adjacent slice of the imaging object, and the selected slice and the adjacent slice may overlap to an extent of greater than 0% and less than or equal to 100%. Another RF pulse corresponding to the angular precession frequency may be applied, to select the same slice of the imaging object, if the subjective determination is that the visual image is of bad quality. Alternatively, the diagnostic information may be tagged, if the subjective determination is that the visual image is of bad quality. In that case, an RF pulse corresponding to a different angular precession frequency

may be applied, to select a respective different slice of the imaging object. The respective different slice of the imaging object may be an adjacent slice in a sequence of slices of the imaging object, and the selected slice and the adjacent slice may overlap to an extent of greater than 0% and less than or equal to 100%. An RF pulse corresponding to a final angular precession frequency may be automatically applied, to select a final slice in the sequence of slices of the imaging object, and an RF pulse corresponding to the angular precession frequency may be applied that corresponds to the tagged image data. The imaging object may be a human being, and the uniform polarizing magnetic field may be produced by a magnetic resonance imaging system. The human being may stand upright within the uniform polarizing magnetic field. After providing the diagnostic information, the imaging object may be moved and an RF pulse corresponding to the same angular precession frequency may be applied, to select a different slice of the imaging object. Moving the imaging object may include changing the angle of the imaging object with respect to the uniform polarizing magnetic field. Each of the 180-degree RF excitation pulses in the sequence may generate a spin echo. Each of the spin echoes may precede a next 180-degree RF excitation pulse in the sequence. The second 90-degree RF excitation pulse may be applied at a center of the spin echo generated by a last 180-degree RF excitation pulse in the sequence. Each of the spin echoes may be encoded differently. At least one of the spin echoes is encoded differently than another of the spin echoes. The second 90-degree RF excitation pulse may



have a phase such that magnetization of the imaging object is forced in the direction of the uniform polarizing magnetic field.

Thus, the multi-echo NMR imaging sequence preferably includes a first 90-degree RF pulse followed by a series of 180-degree RF pulses. The series of 180-degree RF pulses includes  $n$  180-degree pulses, which are followed by  $n$  echoes. A second 90-degree RF pulse is applied at a center of the  $n$ th echo, such that magnetization of the imaging object is oriented in the direction of the uniform polarizing magnetic field. According to the described method, the fast-spin echo technique provides for acquisition of multiple spin echo signals from a single excitation pulse, and spins are driven back to alignment with the polarizing field. Accordingly, image data is acquired more rapidly during a scan, and the time period between scans is reduced.

#### Brief Description of the Drawings

The present invention may be more clearly understood by way of the following written description, appended claims, and drawings, in which:

Fig. 1a shows the timed application of RF and gradient pulses in a conventional/standard spin echo MRI scheme;

Fig. 1b shows the timed application of a conventional driven equilibrium MRI scheme;

Fig. 2 shows the conventional fast-spin echo MRI scheme; and

Fig. 3 shows a fast-spin echo imaging pulse sequence applied with driven equilibrium pulses according to the present invention.

## Detailed Description of the Invention

As noted above, in a conventional spin-echo imaging process, data is collected following the 180-degree RF pulse. Prior to each acquisition, the phase-encoding gradient is stepped according to the conventional spin warp imaging technique. The diagnostic information corresponding to each step of phase-encoding gradient represents a line in the k-space ( $k_x$ ,  $k_y$ ). Once the k-space is filled, a two-dimensional Fourier transform would provide the necessary information to reconstruct an image. A single spin-echo pulse sequence is shown in Fig. 1a. As shown, the sequence includes X, Y, and Z gradients 101, 102, 103, and 90-degree and 180-degree RF pulses 104, 105. The single echo sequence can be expanded to a multi-echo sequence by adding a number of subsequent 180-degree pulses. The time gap between the 180-degree pulses is twice that between the 90-degree pulse and the first 180-degree pulse. This train of 180-degree pulses produces echoes at the center of those RF pulses. The T2 dependence of these echoes can be used to produce a number of images having different contrasts.

A conventional driven equilibrium imaging pulse sequence is shown in Fig. 1b. As shown, the sequence includes X, Y, and Z gradients 106, 107, 108, 90-degree RF pulses 109, 112, and 180-degree RF pulses 110, 111. All the details related to this technique have been described, for example, by van Uijen and den Boef, "Driven-Equilibrium Radiofrequency Pulses in NMR Imaging," Magnetic Resonance in Medicine 1, 502-507 (1984), which description is incorporated

herein by reference. Even though there are two 180-degree pulses 110, 111, only the echo following the first 180-degree pulse 110 is used for image reconstruction. A second spin echo is refocused exactly at the center of the second 90-degree pulse 112. This 90-degree RF pulse 112, applied with proper phase, turns the magnetization to the equilibrium direction.

A fast-spin echo sequence is shown in Fig. 2. As shown, the sequence includes X, Y, and Z gradients 201, 202, 203, a 90-degree RF pulse 204, and a series of 180-degree RF pulses 205. Thus, this pulse sequence has multiple 180-degree refocusing RF pulses, which each generate an echo between adjacent 180-degree pulses. Each of these multiple echoes is then phase-encoded differently, so that the data from each echo fills a different line in  $k_x, k_y$ -space. Fig. 2 shows one exemplary set of phase-encoded levels used in scanning. In this example, there are fifteen 180-degree RF pulses 205 and fifteen echoes following these 180-degree RF pulses. The eighth echo has zero for its phase-encoding amplitude (Y gradient 202). During MRI scanning, each of the phase-encoding amplitudes is stepped so as to generate data from each echo that fills consecutive lines in  $k_x, k_y$ -space. All the data from these echoes make up the entire k-space data needed to construct an image. Fast-spin echo technique is very well described in MRI literature and those skilled in the field of MRI scanning are well aware of its potential. One such advantage is speed, that is, reduction of scan time. Since the entire image is reconstructed from data from all the echoes, the number of echoes during a waiting period determines the number of phase encoded levels acquired in a single waiting period. The

number of wait time (TR) repetitions needed to fill k-space is therefore reduced by the number of echoes in the pulse sequence train. For example, for a 256 phase-encoding level scan with a sixteen echo train, only sixteen TRs are needed to collect the data needed to fill a 256\*256 k-space. Therefore, the scan time is reduced by a factor equal to the number of echoes in a TR. In a multi-slice scan, the slices are interleaved and the pulse sequence is repeated a number of times that is equal to the number of slices.

According to the present invention, an imaging process utilizing application of both the driven equilibrium technique and a fast-spin echo technique can be used to acquire images faster than is possible using either of the two techniques alone. This process can be used in both single-slice and multiple-slice modes. In the single-slice mode, the slices can be obliqued individually. The speed provided by this process is particularly advantageous because a patient does not have to lie still in the scanner as long as with scanners using conventional processes.

An exemplary driven equilibrium fast-spin echo pulse sequence is shown in Fig. 3. As in the previously described sequence, this sequence includes X, Y, and Z gradients 301, 302, 303, a 90-degree RF pulse 304, and a series of 180-degree RF pulses 305. A second 90-degree RF pulse 306 with proper RF phase centered on the last spin echo returns the left over magnetization, determined by the signal strength at the center of the last echo, to the initial equilibrium direction parallel to the background static magnetic field direction. The magnetization requires much less time to recover to its full equilibrium strength compared to a

standard recovery time, which is usually 5 times the T1 value for a given type of tissue.

In conventional fast-spin echo imaging, the contrast is controlled by collecting the central phase-encoding levels (phase-encoding gradient amplitude close to zero) on the echo of choice. For example, the earlier echoes have greater signal from both short and long T1. However, by adjusting TR, one can control the type of image produced by collecting the central phase-encoding levels on the early echoes. For short TRs, T1 weighted images are obtained, and TRs greater than 5T1 produce proton density images. By keeping TRs long (>5T1) and collecting central levels on later and later echoes, greater and greater T2 contrast is produced. The signal-to-noise ratio also varies with TR and effective TE (time to echo on which central levels are collected). For example, T1 weighted fast-spin echo scans have a lower signal-to-noise ratio than proton density images, and T2 weighted images have greater signal-to-noise ratios in longer T2 tissues than in shorter T2 tissues.

Driven equilibrium fast-spin echo, on the other hand, achieves the same signal-to-noise ratio as scans having a TR equal to 5T1. Contrast in the image can be controlled in the same way as it is for conventional fast-spin echo. In addition, greater T1 weighting may be obtained by returning the signal from earlier echoes to the equilibrium direction. While driven equilibrium fast-spin echo and single TR fast-spin echo scans may take approximately same time, the signal-to-noise ratio is much greater using driven equilibrium fast-spin echo than it is using single TR fast-spin echo. This is because the later echoes in a single

TR fast-spin echo sequence have more noise than signal, and therefore reduce the overall signal-to-noise ratio in the image. This is also true for 3D driven equilibrium fast-spin echo scans. The shorter scan time and higher signal-to-noise ratio of driven equilibrium fast-spin echo scans is beneficial in scanning patients with greater anxiety and claustrophobia and in region sensitive to motion, such as c-spine and abdominal areas. The fast single-slice capability is particularly useful when rotation or angulation of slice is necessary to capture the correct anatomy of choice. The speed of driven equilibrium fast-spin echo can achieve the same result with better signal-to-noise ratio in multiple single-slice scans.

Driven equilibrium fast-spin echo, as a single-slice technique, can be beneficial in many ways in scanning different types of patients, in addition to being faster than conventional fast-spin echo techniques. The high speed of single-slice driven equilibrium fast-spin echo can be compared to single-shot ordinary projection X-ray radiograph. The radiographic images are produced immediately, slice by slice, in a cooperative environment between the patient and the scanner operator. This mode of operation can significantly enhance the effectiveness of the scanner utility. It is particularly useful in stand-up MRI systems, where patients have to stand on their feet without moving from the beginning until the end of the scan. In a single-slice driven equilibrium fast-spin echo patient/operator cooperative environment, patients simply walk inside the scanner space, hold one or more handle bars, and stay still only during a single

slice acquisition period. This minimizes patient loading time and time lost due to poor quality scanning.

By taking advantage of the increased scanning speed provided by the process of the invention, driven equilibrium fast-spin echo techniques can be used to scan and image in at least two different single-slice modes: multiple single-slice mode or continuous single-slice mode. In either of these single-slice modes, when the patient moves during a scan, only the slices that are being captured when the patient moves actually show motion artifacts and are required to be repeated, because the entire sequence of slices does not carry the artifact.

In multiple single-slice mode, the patient is told when the acquisition period is to begin, and is asked to remain motionless for the first scan. After data acquisition is completed for the first slice, the patient is notified and allowed to relax. A next acquisition period, for a second slice, then takes place, during which the patient must again remain motionless, followed by another relaxation period. This sequence continues until all slices for the region of interest are individually acquired. The interaction between the scanner operator and the patient during this procedure aids in obtaining motion artifact-free images. This patient/operator cooperative environment allows the patient to relax between slice acquisition periods, and the scanner operator acquires the image data only when the patient is comfortable and rested.

From the scan operator's point of view, each slice is scanned individually, the data for that scan is captured, and the resultant image is presented to the operator on a monitor or other display device. While the patient rests between

scans, the operator can examine the image. If the image shows evidence of movement artifacts, has been corrupted in some manner, or for any other reason is of inferior quality such that a reliable diagnosis cannot be made, the operator can repeat the scan for that slice. The scan may be repeated at that time.

5 Alternatively, the image or some other slice indicator can be tagged for rescanning at some other point in the scan sequence, such as at the end of scanning for the region of interest. The entire process can be cursor-driven, or some other selector can be utilized by the operator to choose particular slices for imaging.

10 In continuous single-slice mode, data is taken for each slice in sequence in an automatic fashion, without the need for operator intervention. That is, the patient is told that the procedure is about to begin, and to remain motionless. The region of interest is then scanned, one slice at a time. These slices are scanned individually, with a predetermined time period between slice  
15 acquisitions. When the last slice data is acquired, the procedure ends, and the patient can relax. If the patient moved during acquisition of any of the slices in the automatic sequence, artifacts may be evident in the images associated with those slices, but not in any of the images associated with slices acquired while the patient did not move. The slices associated with the artifact images can be  
20 identified, and acquisition of those individual slices can be repeated so that the resulting artifact-free images can be used to replace the images having motion artifacts. This procedure is particularly beneficial to throughput-conscious scanning centers, because only image data for particular slices in the sequence



need be reacquired. In contrast, when a conventional multiple-slice scanning technique is used, all slice images show motion artifacts when the patient moves, and therefore acquisition of all the slices must be repeated if the patient moves at any time during the entire scan sequence.

5 From the scan operator's point of view, as each slice is scanned individually in automatic sequential fashion, the data for that scan is captured, and the resultant image is presented to the operator on a monitor or other display device. The scanner moves in sequence from slice to slice, according to preset parameters that determine, for example, slice width and degree of slice overlap. 10 Thus, once the system is activated, the scans are performed one slice at a time, and images are presented to the operator in sequence. If the image currently being presented shows evidence of movement artifacts, has been corrupted in some manner, or for any other reason is of inferior quality such that a reliable diagnosis cannot be made, the operator can tag the image or can earmark some 15 indicator of that slice. The tagged slices can be rescanned at some other point in the scan sequence, such as at the end. The rescanning process can be cursor-driven, or some other selector can be utilized by the operator to choose particular slices for repeating the scan process.

Using driven equilibrium fast-spin echo techniques enables the use of 20 either of these single-slice modes, which can further enhance the effectiveness of stand-up MRI systems. By providing a number of rest periods for the patient in the multiple single-slice mode, and by diminishing the consequences of patient movement in both modes, two of the main drawbacks of stand-up MRI

procedures are eliminated. Conventional multiple-slice imaging may be more efficient in providing a larger extent of coverage in a given amount of time, but only if the patient never moves during the entire scan sequence. If the patient moves even once during the procedure, artifacts will be present in all the images, the entire procedure will have to be repeated, and the multiple-slice advantage becomes a detriment.

There are two ways of running the multiple single-slice mode. In the first type of procedure, the region of interest is placed in the center of the magnet and imaged using driven equilibrium fast-spin echo. After that slice is imaged, the patient bed is moved to position the next region of interest in the center of the magnet, and that region is imaged as before. By following this procedure, the Larmor frequency remains constant, that is, it is not changed to excite different slices. This mode of operation significantly reduces the stringent and harder to achieve specification requirements of a whole body scanner. Accordingly, this can reduce the cost of the MRI scanners themselves, and make it more affordable for a larger percentage of the population to undergo MRI diagnosis. This mode of operation can be called the CAT Scan mode of operation because of the similarity of operation of the two diagnostic modalities. According to the present invention, use of this mode does not limit the operator to axial plane imaging only; coronal plane imaging, for example, may be obtained by tilting the bed and the gantry. Through tilting of the patient platform, different slice angles over the same region of interest can be applied in other diagnostic situations as

well. In other applications, the main magnetic field can be suitably reconfigured to image other planes.

In the second multiple single-slice mode type of procedure, the conventional whole body magnet space may be used either for volumetric-driven equilibrium fast-spin echo or repeated single-slice imaging with driven equilibrium fast-spin echo. In this case, the Larmor frequency is adjusted to match the slice select gradient and the position of the next region of interest, and the patient may remain stationary. This may be repeated until all the required slices are acquired. In the volumetric or 3D acquisition procedure, the conventional stepping second phase-encoding gradient is used along the slice/slab selection direction. A 3D Fourier Transform (3DFT) may be used to reconstruct the final images.

In both types of procedure, individual slices or slabs may be oriented to image the anatomy of interest. Imaging the multiple single slices with their respective individual slice orientations is particularly useful in obtaining both T1-weighted and T2-weighted images with greater speed and accuracy.

Only one frequency is used for excitation in acquiring the NMR signal in the single-slice mode. Gradients are adjusted for oblique scanning. Once that slice is completely acquired, the NMR frequency and the gradient are adjusted to acquire an image from a different region with a second oblique angle. The greater speed of single slice acquisition is beneficial to the patient, who can relax between slices.

In the simultaneous multiple-slice acquisition mode, in contrast to conventional sequential multi-slice mode, RF phases of different slices are different from one another and the final images can be constructed either by sharing the  $k_y$  space or by using a third fast Fourier transform to separate the slices. All the slices have the same oblique angle.

Thus, in general, the fast-spin echo technique utilized is essentially a multi-echo NMR imaging sequence, where different echoes are encoded differently to fill the  $(k_x, k_y)$  space at a speed of  $1/n$  of the single echo speed, where  $n$  is the number of echoes in the multi-echo sequence. During this echo train, a 90-degree RF pulse applied with proper phase at the center of any echo turns the magnetization back in the direction of the static magnetic field. The amount of returned magnetization is a function of how late in the echo train the 90-degree RF pulse is applied. Within a short waiting time after the 90-degree RF pulse, the spins are ready to be excited again. The substantial reduction in the waiting time  $TR$  results in faster scans, and in the single-slice modes, the scans can be obliqued to fit the anatomy of choice.

The driven equilibrium fast-spin echo technique also allows positioning of slices such that they are closer than with conventional scanning techniques. Driven equilibrium fast-spin echo in either single-slice mode does not saturate the signal-producing spins, regardless of the degree of proximity or even overlap of adjacent slices in a sequence. As a result, adjacent slices can be scanned such that they overlap to any degree, from 0% to 100%. This means that the anatomy can be imaged better than when using conventional techniques, and

details that would be lost due to volume averaging in a conventional procedure are detected in closely spaced/overlapping adjacent slices.

Scanning the region of interest in multiple single slices with varying degrees of overlap (0% to 100%) can provide anatomic details that facilitate diagnosis of the patient's ailment. The single-slice modes of the present invention provide even greater advantage when utilized in stand-up MRI systems, which show greater detail in anatomical areas such as c-spine, t-spine, and l-spine discs and vertebrae, as well as with problems involving shoulder dislocation, and knee and ankle area injuries. Scanning these areas with overlapping slices was not possible conventionally, without significant loss of signal-to-noise ratio. Driven equilibrium fast-spin echo overcomes this barrier and provides anatomical imaging detail that otherwise might be missed by slices incorrectly positioned, and/or due to volume averaging in the slice thickness direction, in conventional scans.

To summarize, a general multi-echo sequence has one 90-degree RF pulse in the beginning, followed by a series of 180-degree RF pulses. If there are  $n$  180-degree pulses, then  $n$  echoes follow those 180-degree pulses. A second 90-degree RF pulse is turned on exactly at the center of the  $n$ th echo, which returns all the magnetization left at this time to the static field direction. All the gradients used in imaging have to satisfy the standard integral condition up to the center of the second 90-degree pulse. Careful adjustment of integral conditions minimizes loss of signal-to-noise ratio.

A driven equilibrium fast-spin echo technique therefore overcomes the shortcomings of both conventional fast-spin echo techniques and driven equilibrium methods, resulting in greater signal-to-noise ratio, scanning speed, and contrast control. The process of the present invention provides both single slice and multiple slice capabilities, and allows for individual slice orientation and simultaneous multiple slice scanning. Proper utilization of the technique reduces demand on the magnet, at least in part by reducing the required gradient power, resulting in less expensive scanner hardware and a more cost-effective scanning process. The utility and efficiency of particular MRI procedures, such as stand-up image scanning, are enhanced. While these improvements and advantages are certainly noteworthy, it is important to recognize that 3D Fourier transform spin echo scanning techniques are only possible using the process of the present invention, and are not even contemplated through the use of conventional spin-echo scanning processes.

The processes described above, utilizing driven equilibrium techniques, can increase the speed of multiple-slice scanning, particularly in areas of anatomy that usually require a smaller number of slices, such as in the region of the sagittal suture, and along the cervical/thoracic/lumbar vertebrae. The reduced TR realized by a driven equilibrium fast-spin echo sequence, compared to that of a convention fast-spin echo sequence, can reduce an overall scan time by several minutes.

Further, the driven equilibrium fast-spin echo technique as described, combined with a simultaneous multiple-slice capability, can reduce scanning time

in imaging situations requiring a large number of slices, such as in head, abdomen, and knee scans. For example, head scans, which can typically require 20 to 24 slices for full coverage, have TR values that cumulatively result in quite long scan periods. Using driven equilibrium fast-spin echo techniques according to the present invention reduces this scan time by the number of echoes in each TR, as noted previously. Thus, this simultaneous multiple-slice mode makes scanning and imaging such anatomical regions much more bearable for the patient.

The present invention has been described by way of example and in terms of preferred embodiments. However, it is to be understood that the present invention is not strictly limited to the particularly disclosed embodiments. To the contrary, various modifications, as well as similar arrangements, are included within the spirit and scope of the present invention. The scope of the appended claims, therefore, should be accorded the broadest possible interpretation so as to encompass all such modifications and similar arrangements.